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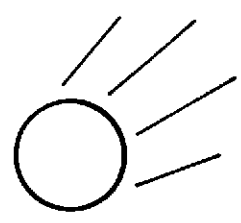
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**THE 1973 REPORT AND RECOMMENDATIONS
OF THE
NASA SCIENCE ADVISORY COMMITTEE
ON
COMETS AND ASTEROIDS**



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"A PROGRAM OF STUDY"

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SECTION I

INTRODUCTION

1.1 SCOPE OF THE REPORT

This 1973 report provides a sequel to last year's report, "Comets and Asteroids; A Strategy for Exploration." The previous report was broad in scope. The intent here is a narrowing of the scope to emphasize scientific objectives and to recommend the development program needed to provide instruments to achieve them. The justification for comet and asteroid exploration is strengthened, and recommendations regarding specific mission opportunities and developments are made.

An annotated bibliography is included to reference reports which provide technical details on various flight missions and execution modes.

1.2 COMETS

1.2.1 Basic Knowledge Limits

The astronomer defines a comet, as distinct from an asteroid, not by its highly elongated orbit about the sun, but by the fact that it looks fuzzy to the eye or on a photograph. At great distances from the sun, some faint comets appear completely stellar and thus indistinguishable from asteroids, but few are seen beyond Jupiter. All these are, within measurable accuracy, gravitationally attached to the sun. J. Oort suggested that a passing star occasionally penetrates a great cloud of comets orbiting around the sun like a bullet passing through a swarm of gnats. Some comets disappear each time, but a few are disturbed into randomly oriented orbits toward the sun, where the solar heat activates them. In an alternative theory advanced by Axford and Wetherill, a reservoir of comets is located nearer the sun, in the outer reaches of the known planetary system. The planets, particularly Jupiter, perturb the comets, throwing some of them out of the system and others into short-period pro-grade orbits. Thus, some comets have extremely long-period orbits, too long to be measured, while others like Comet Encke (with the shortest period, only 3.3 years) move entirely within Jupiter's orbit.

As comets approach the sun, they become brighter and fuzzier, the brighter ones developing tails of two classes, ion and dust. Spectroscopy and photometry show that the haze about the head of a comet results from gases and dust that are lost forever from the comet.

The Orbiting Astronomical Observatory (OAO-2) and other space probes have detected an enormous ejection rate of hydrogen and OH from three comets. The brightest, Comet Bennett (1969 i), comparable to Halley's famous comet, ejected hydrogen at a rate corresponding to 40 tons of water per second, according to A. D. Code and B. D. Savage. This adds up to a good fraction of a cubic kilometer of H_2O during the passage of the comet about the sun. Such copious loss of substance strongly supports Whipple's dirty-ice model for cometary nuclei. This theory was developed to explain the observation that comets deviate from Newtonian motion about the sun. Halley's Comet, for example, increases in period by some 4 days per period (76.1 years) according to recent results by T. Kiang, while B. Marsden has shown that most short-period comets are changing period, some positively and others negatively. The jet action of solar-vaporized ices from a rotating comet nucleus can provide the force needed, if enough ice such as frozen H_2O is available. The molecules observable in the head of a comet as seen from the ground — C_2 , C_3 , CH, CH_2 , CN, NH, NH_2 , and OH — are not abundant enough to provide the necessary force. We know from space studies that comets do lose enough gas to make the jet forces adequate.

The outgoing gases from comets become ionized and are forced away from the sun by the solar wind. Often this phenomena is visible in spectacular ion tails, stretching for many millions of kilometers. The observed ions are those of CO, CO_2 , CH, N_2 , and OH. From earlier space exploration we know with certainty that the solar wind of electrons and ions carries magnetic fields from the sun. The fields may drag the ions from the head into the cometary tail, leaving behind the neutral atoms and molecules. Thus, a comet is a laboratory of collisionless plasma interactions. Measures of the magnetic fields and ion motions near the head of a comet will provide direct knowledge of these interactions which the plasma physicist currently find difficult to predict theoretically.

The more highly curved comet tails (dust tails) show a continuous spectrum of particle sizes, which, with other observations, proves that they consist of fine dust forced away from the comet, first by the outflowing gas, and then by the pressure of solar radiation. Presumably, the dust is primitive, collected along with the ices in the formation of the comets. Larger aggregations of the dust constitute meteoroids, which often provide spectacular showers when the earth's orbit nearly crosses that of a sizeable comet. Meteor studies show that meteoroids are fragile bodies, no doubt easily crushable between the fingers, mostly less dense than ice and probably of cometary origin.

Almost certainly we have, in the fine particles left by meteors and fireballs after they disintegrate in the upper atmosphere, samples of comets on earth. But the atmospheric entry problem makes the Earth-based study of cometary dust very unsatisfactory. It is also possible that one type of meteorite, the carbonaceous chondrite type 1, comes from a comet. These meteorites very nearly have the correct solar composition for all but the more volatile materials such as the rare gases. The carbonaceous chondrites evidence a minimum of heating since the time when they were formed at rather low temperatures. Also, they contain complex organic compounds, difficult to distinguish from some biological forms.

It is important to know whether the nucleus of a comet contains solids like the carbonaceous chondrites. Certainly the spectra of comets show an amazing distribution of unstable molecules or radicals, all made of H, C, N, and O. Most radicals may derive from more stable molecules such as methane (CH_4), ammonia (NH_3), and carbon dioxide, probably trapped in ordinary H_2O snow, as suggested by P. Swings and A. Delsemme. Much more exotic stable molecules, such as are now observed in deep space by radio, must also be present. The common earthly atoms Na, Ca, Cr, Co, Fe, Ni, Mn, Cu, and V show up in the spectra of comets very near the sun, the "sun grazers." The other expected atoms like Si appear in the spectra of meteors from the fragile cometary meteoroids. Thus, chemically, a comet nucleus could well contain both the earthly atoms of carbonaceous chondrites and also the complex organic compounds, including less stable ones.

We know that observed comets are disintegrating. Some, such as Biela's and the sun grazing comets have broken up, almost literally before

our eyes. But what really happens to them when they expend their ices and finally "die?" Is there a residual core of meteoritic material? Or, do some of them, or indeed all of them, finally end their lives as dissipating wisps of dust and gas? Some of the large short-period comets, like Encke's, give some evidence of having meteoritic cores. If so they may end up looking like asteroids and contributing to the group of small asteroids that cross the earth's orbit. The prototype of this group is Apollo. A dozen observed Apollo asteroids suggest that 100 or 200 unobserved kilometer-sized asteroids cross the earth's orbit. How many, if any, are old cometary nuclei?

We know that comet nuclei range from less than a kilometer in diameter to tens of kilometers for the brightest ones, but we still have no accurate measures.

Understanding the fate of old cometary nuclei will go far in defining the mechanisms of cometary origins. If they finally dissipate completely they must have been made from the accumulation of particles composed both of dust and ice, i.e. something like interstellar grains on which ices and radicals accumulated. Such accumulation must have taken place in a low density region (high density as interstellar clouds go) where the temperatures were very low.

If comets generally have meteoritic cores, on the other hand, they may have formed by the slow cooling of a relatively hot and dense gas cloud allowing time for the aggregation of earthy material before the ices and remaining dust collected about the meteoritic nuclei. This situation could have occurred at the outskirts of the generally postulated primitive solar nebula. Such comets could have collected to form the outer planets Uranus and Neptune (and Pluto?). Very rapid cooling might also have produced these planets, but then comets should not have developed sizeable meteoritic cores unless a large amount of short-lived radioactivity sublimated the inner ices.

A definitive answer on comet origins requires definitive knowledge about cometary nuclei.

1.2.2 INVESTIGATIVE STRATEGIES

Observations from the Earth or in space from near the Earth show little promise of solving the enigma of comets. We must go to them by means of instrumented space probes.

A cometary probe has, as one of its first objectives the determination of the dimensions of the hypothesized nucleus by direct observation. The relatively small surface area of the nucleus (perhaps less than 1 km^2) reflects so little sunlight that the haze of escaping dust and gas obscures it when seen at earth distances. Up close, it should become visible. Otherwise, complete obscuration would keep sunlight from reaching the surface, and sublimation would stop. A space probe near a comet can measure the diameter of the nucleus either by direct television or by a slit photometer rotating with the space probe. Both may be able to determine the period and axis of rotation.

The mass of a comet nucleus will be difficult to determine, however, because the radial force from the outflowing gas will more than overcome the gravitational attraction for a nearby spacecraft.

Hence, a gravity-gradient measuring device may be the only direct method of measuring the mass. Knowledge of the mass, and hence density of a dimensionally known nucleus, will lead to strong implications regarding its composition.

A comet probe also determines the nongravitational motion of a comet on a relatively short-time basis. On-board instruments can possibly measure the velocity, direction, and amount of gas ejection simultaneously to determine the resultant force.

The outgoing gas could make the ultimate in cometary missions, a landing, uniquely difficult. But before attempting a landing, we should utilize the comet as a tremendous physical laboratory offering a wide range of important environmental experiments in molecular physics, molecular chemistry and plasma physics.

On the molecular side we must identify the parent molecules of the radicals and ions that appear so prominently in the spectra of the coma and ion tail. So far only H_2O is virtually certain as a parent molecule. What are the actual hydrates imbedded in the so-called clathrates of Swings and Delsemme? The molecules must be both abundant and highly volatile to activate comets such as Kohoutek at 4.7 AU from the sun, where the vapor pressure of H_2O ice is negligible. Surely these parent molecules must be

blowing out H_2O dust to produce the hazy comas of such comets. Mass spectrometers and spectroscopy (in both the ultraviolet and infrared) are clearly required to solve this problem.

In plasma studies, the interaction between a cometary atmosphere and the solar wind may result in a strong collision-less shock, or possibly charge exchange may occur in such a way as to decelerate the solar wind smoothly, resulting in no shock at all. Certainly the huge accelerations observed in ion tails require a hydromagnetic interaction between the solar wind and the comet. Radiation pressure is completely inadequate. Equipped with a variety of instruments, a flyby vehicle under proper conditions can measure molecular weights in order to identify the atoms, ions, and parent molecules, while also establishing the processes affecting these ejecta from the cometary nucleus, namely, excitation, dissociation, and ionization by solar radiation, by the solar wind and by the magneto-hydrodynamic interactions which create the observed structure of coma and tail. A flyby vehicle can also measure the velocities, numbers and properties of solid particles accompanying the gas, and it can conduct photometric observations of various kinds.

In summary, the comet can be broken into specific areas of scientific interest as follows:

a. Nucleus

Detailed study of the nuclei of comets is required to determine the place, time, and processes involved in their origin, to determine their subsequent histories, the current mechanisms of phenomena, and to obtain evidence relating these processes to the properties of planets. At the present time, the topographical dimensions, density (mass), optical properties, rotational period and axis of cometary nuclei are essentially unmeasured and only surmised. The basic chemical compositions of the nucleus, is only vaguely understood, as is its basic physical structure. Correlation of its properties with the orbit and place of origin of the attendant phenomena constitutes a legitimate area of study. Of all the features attributed the nuclei of comets, only the order of magnitude of nongravitational motion is perhaps fairly well known but its true cause remains a mystery.

b. Coma

To obtain knowledge of the coma it is necessary to understand the chemical processes resulting from interaction of the outflowing gases with solar radiation. Investigation of the gases in the coma should reveal the composition and abundance of parent molecules (now virtually unknown) and of neutral and ionic product species, but little understood at this time. The motions of molecules, radicals and ions also are but vaguely understood. On the other hand, our present knowledge is considerable regarding certain solar effects on gases; for example, the theory for the dissociation and ionization processes induced by solar radiation is well known, though parameters are uncertain. However, a theory pertaining to the dissociation and ionization processes induced by solar charged particles is being developed, and is yet untested.

Solid particles in the coma offer further field for study. The list of unknowns includes the composition, density, and the relationship of particles to known classes of meteorites. The distribution of particles with respect to size and the optical properties of these particles is but vaguely understood. However, the gross motions of particles are fairly well known.

c. Dust Tail

Investigation of the dust tail of comets would reveal knowledge of its composition, density, and relationship to known classes of meteorites. Again, details of the size and distribution of dust and its optical properties are little understood even though the gross motions of dust are fairly well known.

d. Ion Tail

The ion tail of comets constitutes a natural space plasma laboratory. Here it may be possible to learn in depth, the intricacies of basic plasma physics. Areas of emphasis would be the aforementioned ionization and dissociation mechanisms, interaction with solar wind, and energy-momentum transfer processes. All relate to theories now under development. Only the gross composition and motion of tail ions is relatively well understood at present.

1.3 THE GOALS OF ASTEROID EXPLORATION

Most of the asteroids move in rather circular orbits between Mars and Jupiter, not much inclined (10 deg on average) to the orbital planes of the planets. A few, called Trojans, remain trapped, through perturbations caused by Jupiter, in Jupiter's orbit some 60 deg ahead or behind the great planet as seen from the sun. Several dozen are known to cross the orbit of Mars, and, as previously noted, another dozen or so, the Apollo asteroids, cross earth's orbit. A few move in more highly inclined and eccentric orbits like those of some short-period comets, but none move retrograde or opposite to the direction of planetary motions. We know the orbits fairly well for about 2000 asteroids out of approximately 50,000 that could be observed given the manpower, instruments, and motivation. The smallest that could be seen would have a diameter ranging from less than a kilometer to a very few kilometers.

We have a fragmentary knowledge of asteroids. Vesta has the best known diameter, determined from polarimetry and interferometry measurements, but the uncertainty in the density even for this large asteroid ranges from 2.0 to 2.8. We can only estimate the sizes of the smallest asteroids from their brightness by assuming their reflectivity. Photometry, polarization measures, and spectroscopy can give us only intriguing but not definitive answers as to reflectivity, and therefore dimensions or composition.

All asteroids undoubtedly have received a merciless pummeling from encounters with smaller bodies, as evidenced in the pictures of Mars satellites, Phobos and Deimos, made by Mariner 9. Cratering and breaking by collisions will expose surfaces in the asteroids analogous to the walls of the Grand Canyon. Many asteroids must be greatly disfigured, as is evident from variations in their brightness as they rotate. Some appear to be highly elongated. Some rotate so fast that they must be held together by their own internal strength.

The great interest in asteroids is stirred by the probable cast-off fragments, the meteorites. Modern laboratory studies give us a wealth of information about the meteorites increasing the incentive to identify their parent bodies. Modern radioactive techniques have shown not only that most

meteorites were formed 4-6 billion years ago, but also that their unknown parent bodies were heated to various levels below or near melting, then cooled, all in only 100-300 million years after formation. Even the iron meteorites, as shown by J. A. Wood and J. I. Goldstein, cooled at rates of 1-10 deg per million years. This rate is typical only for bodies with diameters of hundreds of kilometers. This leaves us with a real mystery as to the short-lived heating mechanism, and belies the concept that many of our meteorites come from moon-sized objects, none of which now exists among the asteroids.

J. H. Reynolds and his students have uncovered even more intriguing information. They find that the meteorites gained a significant number of newly made atoms at the time of their agglomeration. Some meteorites show excesses of xenon-129 as compared to other solar-system abundances, attributable only to the decay of radioactive iodine-129 with a half-life of only 17 million years. Further, plutonium-244 (half life, 80-million years) also apparently contributed to the xenon isotopes. These results, coupled with astronomical observations, support the concept that the sun and solar system formed in a large collapsing cloud of interstellar gas and dust, possibly along with a large star that blew up as a supernova and produced new atoms which were subsequently incorporated into the solar system.

The parent bodies of meteorites probably formed well inside the solar nebula in the general neighborhood of the terrestrial planets, where the temperature was high enough to prevent H_2O from freezing.

Direct evidences of fossil solar activity, but of unknown intensity, appear in some meteorites as rare gases or as fossil tracks of high energy particles on crystal boundaries. To interpret these observations and explain details of condensation and agglomeration, the origins of the meteorites must be determined.

Clearly, we must go to the asteroids to find the answers.

Our situation today is much as though a geologist were given a large number of samples selected randomly from the walls of the Grand Canyon in Arizona and perhaps some other localities in addition without any information as to the original position of the individual samples. His task of reconstructing

the stratification history of the Grand Canyon from such samples would be comparable to that facing the meteoriticist today. He must reconstruct both the temporal and the solar positional variables during the period of planetary accretion in the solar system.

Close-up television imaging can give us dimensions and topography as well as information on surface structure ("geology") to help with deciphering the Grand Canyon problem. Rotating slit photometry can do the similar tasks perhaps with less resolving power. Either method should tell us the rotation period and axis.

To get the mass of the largest asteroids (about 750 km in diameter) we can exploit precise radio tracking of a probe's motion during a reasonably slow flyby. The observed bending by the gravitational forces would provide the needed information. A gravity-gradient measuring instrument should work admirably on smaller asteroids (>1 km) if the observation time is extended, perhaps in a rendezvous mission. Knowledge of density would follow from such measures of dimensions and mass.

A docking mission would provide direct studies of the mineralogy, surface structure, and composition of the asteroids. One can do better with sample returns but at much greater cost.

In summary, the goal of space exploration of asteroids is to determine their nature and history, and to obtain evidence relating to the process of planet formation in the solar nebula.

Areas and measurements supporting this goal include:

- (1) Dimensions
- (2) Density
- (3) Surface structure and optical properties
- (4) Basic-chemical (mineralogical) composition
- (5) Basic physical structure (stratigraphic record of accretionary processes in solar nebula)

- (6) Isotopic composition and radiometric age
- (7) Rotation period and axis
- (8) Relationships to known classes of meteorites
- (9) Magnetic properties
- (10) Relationships (if any) to old comet nuclei
- (11) Correlation of chemical and physical properties with formation processes and later evolution.

Of the above, all but the rotation period and axis of certain asteroids is either unknown or at best vaguely understood at the present time.

1.4 SPACE MISSION PRACTICALITY

Numerous studies of space mission implementations show that present-day technologies make flyby missions to comets and asteroids entirely feasible. (See Bibliography) On a comet mission, a path can be designed to closely approach one or two asteroids on the way. Thus, a single mission can address both comet and asteroid objectives. Accurate tracking of asteroids by classical ground-based techniques makes possible passes to a few hundred kilometers or so. The relative speeds on such enroute asteroid flybys will, however, be high (≈ 10 km/s). For comets, the uncertainty in position introduced by non-gravitational forces will probably require terminal guidance maneuvering to achieve low miss distances. (>1000 km) On the other hand, the velocities of comet flybys can range from less than 7 km/sec using solar electric propulsion techniques, up to 55 km/sec, the latter for ballistic passes of retrograde-moving comets such as Halley's. High velocities tend to create a real and uncertain hazard from collision with meteoritic material ejected by comet nuclei and make instrumentation to measure in-situ characteristics complex and costly.

The highly desirable low speed, and rendezvous and/or docking missions to comets and asteroids require more sophisticated propulsion systems on-board the vehicle than conventional solid or liquid rockets. Controllable ion propulsion by means of solar electric or nuclear power is indicated and, must be developed to provide the needed capability for comet and asteroid exploration.

In the meantime, ballistic missions have been proposed. A highly desirable mission to comet Grigg-Skjellerup with continuation to comet Giacobini-Zinner can be made well within this decade (1977-1979) (Ref. 1. Ness and Farquhar). It requires only a positive administration decision and adequate financing.

Attractive follow-on missions which take advantage of comet Encke's short period are also available. This comet offers a unique pair of opportunities in 1980 and 1984. A scenario including the above-mentioned electric propulsion technique to provide a slow flyby in 1980 and a rendezvous in 1984 has been proposed (Ref. 2. Atkins and Moore). Ballistic alternatives for the 1980 opportunity are also under study.

Another highly desirable mission, both to the scientist and to the public, will be to Halley's Comet during its 1986 approach to the sun. This great comet was well observed by the Chinese in the pre-Christian era and made a spectacular solar passage in 1910. Its motion, within 20 deg of absolute retrograde to the planetary motions, makes low speed flyby or rendezvous with it almost impossible unless nuclear electric propulsion is used. A fast flyby, however, could give us rare new insight as to the nature of this ancient visitor from beyond Neptune's orbit if reasonable science could be done at the attendant 35-55 km/s speeds.

Instruments for most of the scientific measurements suggested have previously ridden in the many space probes, planetary, and lunar missions already carried out, although the relative speeds have been less than 12 km/s. Thus, the scientific experiments for missions to comets and asteroids can consist mostly of existing designs, already tested, with modifications only for indicated improvements and compatibility. Terminal guidance for rendezvous or landings will pose challenging problems but does not appear to require new fundamental developments, so long as highly controllable propulsion systems become available.

Weight requirements and the number of scientific experiments in a mission depend on funding and propulsion systems. Not all desirable experiment. could fly in one mission.

1.5 THE IMPORTANCE OF AN EARTH-BASED OBSERVATIONAL PROGRAM

A significantly expanded ground- and space-based observational program will be essential to an effective program of missions to comets and asteroids. Successful flybys of comets and asteroids demand the limit of precision available in positional and orbital determinations, particularly for the former. Today, in the U.S., we depend mostly on one astronomer, Elizabeth Roemer of Tucson, Arizona, for comet observations. Because of nongravitational motions, observations of comets approaching the sun must begin at the greatest possible distances, which means with telescopes with apertures in the 70-100 in. range. Otherwise, we may not be able to predict positions accurately enough for the desired close range flybys.

Special telescopes devoted to comets and asteroids are clearly needed, at least one for each hemisphere, and we must encourage more observers to enter this field.

A significant furthering of physical understanding of comets prior to in-situ space missions can be obtained from the ground, both by observation and from theoretical studies. From earth-orbiting observatories can come much needed knowledge of physical processes in comets and information concerning some parent molecules which can provide a correlation basis for highly effective flybys, rendezvous, and dockings. This preparatory research will greatly increase the science return from space missions and aid in selecting optimum experiments and strategies.

For asteroids, only a beginning has been made in carrying out systematic photometric observations of brightness, rotation, polarization, colors, and spectra. Detailed studies of a number of asteroids will provide taxonomic data of critical value in associating types of asteroids with types of meteorites, a correlation basic to solving the "Grand Canyon" problem. The limited photometric studies of asteroids to date show an enormous range in color, albedo (reflecting power), polarization, and spectrum. Asteroids are not alike. Many classes and subclasses are beginning to appear. Some, like the second brightest, Vesta, reflect excellently with an albedo of the order of 0.20 or more, compared with the moon's albedo of only 0.07, which fairly well

typifies asteroids. Some appear much blacker than the moon. We sorely need more data on asteroids in order to make optimum selections for space missions so that the objective of calibration can be fully attained. Hence, a commanding need exists for special telescopes and programs devoted exclusively to the study of comets and asteroids.

1.6 BACKGROUND RESEARCH RELEVANT TO COMET AND ASTEROID MISSIONS

The astronomical and space communities have collaborated actively in realistic planning for missions to comets and asteroids. In March 1971, an international symposium held at Tucson, Arizona, led to the volume Physical Studies of Minor Planets (NASA SP267) edited by T. Gehrels and published by NASA in 1971. A cometary Science Working Group hosted by C. R. O'Dell met at Yerkes Observatory in June 1971 to analyze the astronomical science and the space technology of cometary missions. IIT Research Institute, with the support of NASA/OSSA, published the Proceedings of the Cometary Science Working Group edited by D. L. Roberts. The initial concept of a mission to Comet Encke in 1980 comes from this publication. A conference on comets and space missions to comets met in 1970 at Tucson, Arizona. The proceedings, edited by E. Roemer and G. P. Kuiper, are published under the title Comets, Scientific Data and Missions, Lunar and Planetary Laboratory, Univ. of Arizona, 1972, supported by NASA.

The proceedings of two important relevant symposia in Europe have recently been published: Nobel Symposium No. 21, From Plasma to Planet, edited by Aina Elvius, Almquist and Wiksell, Stockholm, 1972; and On the Origin of the Solar System, edited by Hubert Reeves, Centre National de la Recherche Scientifique, Paris, 1972.

The predecessor of this Committee, the Comet and Asteroid Mission Study Panel, headed by Ernst Stuhlinger of the NASA Marshall Space Flight Center studied the science and technology of missions to small bodies in the solar system. They have summarized their conclusions in a document Comets and Asteroids, Strategy for Exploration, now available from NASA Headquarters as NASA TMX-64677.

In addition a number of valuable studies of specific mission possibilities have been produced within NASA and under contract with NASA. (See Bibliography).

SECTION II

PRIMARY EXPERIMENTS AND INSTRUMENTS

2.1 IMAGERY

The recent imaging of Phobos and Deimos during the Mariner/Mars 1971 mission was impressive. Even though the resolution was not more than about 300 lines over the surface, much was learned from the pictures. Images have a conceptual value relating to general science and to specific detailed studies. A precise measurement of the size and albedo of these bodies was obtained and we learned of their exceptional roughness and saw the effects of bombardment by surprisingly large bodies. In more detailed studies the precise figure of the satellites has been obtained and also the orientation of the rotation axis in space. Both Phobos and Deimos were found to rotate synchronously in their orbits about Mars.

The ability to resolve and photograph any solid nucleus is the principal objective of any comet imaging experiment. Imaging serves two functions during cometary missions: 1) science, and 2) approach guidance. The approach guidance function arises from the scientific imaging requirements on the following way. For some comet missions, the nominal uncertainty (1σ) in the position of the nucleus at launch is $\sim \pm 30,000$ km. Midcourse correction based on ground-based observations of the comet's trajectory after launch can typically reduce this uncertainty to ~ 1000 - 5000 km. In exceptional cases (e.g. Grigg-Skjellerup, 1977) unusually favorable viewing geometry can reduce the uncertainty to ~ 100 km. Scientific imaging requires a sun-illuminated view of the nucleus at periapsis. A trajectory giving reasonable assurance of proper illumination might take the spacecraft to within 3σ of the nucleus, i. e. at a flyby distance of from 300 km to $>15,000$ km depending on the particular mission. Imaging at the high end of this range would require a lens of more than 5 meters focal length. Such lenses are probably beyond the support capabilities of Mariner and Explorer - class spacecraft. Shorter, more practical focal lengths require reduced miss distance, which can be achieved with final trajectory corrections using data taken from optical approach

guidance. The only mission identified so far for which approach guidance is not necessary is the Grigg-Skjellerup (1977) mission.

The objective of imaging should be to resolve any nucleus having a diameter of at least 1 km. The actual quality of the image will be highly dependent on the nature (solid, swarm-like) of the actual nucleus. The nucleus will have been resolved if the image occupies 3 to 5 picture elements along the smear direction for at least several frames.

There are presently two types of imaging systems (i.e. TV, spin-scan) available for use on 3-axis stabilized and spin-stabilized spacecraft, respectively. The television imaging systems are exemplified by the very successful system used on the Mariner/Mars 1971 spacecraft. Typical parameters for this type of camera are shown in Table 2-1. Some components could be further optimized for a comet mission.

2.2 SPECTROMETRY

2.2.1 Mass Spectrometry

The great value of the mass spectrometer for studies of comets lies in its ability to detect molecular and atomic species that are inaccessible to remote optical spectroscopy, to determine the abundance of these species and to evaluate isotopic ratios. Of particular interest is the search for so-called parent molecules in the immediate vicinity of the nucleus and an investigation of the possible presence of noble gases, including a characterization of their isotopic composition. Other important isotopes include ^{13}C and ^2H , and a search for simple sulfur compounds would be of great importance for defining the relationship between comets and meteorites.

A list of presently identified molecules in cometary spectra is given in Table 2-2 (Ref. 3. Arpigny, 1972). In postulating parent molecules for some of the radicals listed here, it is helpful to consider a comparable listing of molecules in Table 2-3 that have been identified in the interstellar medium (Ref. 4, Solomon, 1973). Inspection of these tables reveals that there are usually several candidates for each of the cometary radicals. It is of course not yet established that comets condense directly out of unmodified, low

Table 2-1. Mariner 71 Camera Parameters

	A Camera Wide Angle	B Camera Narrow Angle
Effective focal length	150 mm	600 mm
Focal ratio	f/0.75	f/3.0
Approximate fastest shutter speed		20 msec
Angular field of view	3.7 x 4.8 deg	0.92 x 1.19 deg
Active target raster	9.6 x 12.5 mm	9.6 x 12.5 mm
Aspect ratio	1.30:1	1.30:1
Active scan lines per frame	700	700
Frame time	42 sec	42 sec
Total line time	60 msec	60 msec
Active line time	56.6 msec	56.6 msec
Line sync time	3.4 msec	3.4 msec
Approximate black mask time	1.0 msec	1.0 msec
Active picture elements per line	832	832
Bits/picture element	9	9
Video carrier frequency	28.8 kHz	28.8 kHz
Video base band	7.35 kHz	7.35 kHz
Video sampling frequency	14.7 kHz	14.7 kHz
Video pass band	21.45 to 36.15 kHz	21.45 x 36.15 kHz
Lens weight	13.7 kg	9.1 kg
Camera head weight	3.1 kg	3.1 kg
Bus electronics weight	1/2 of 6.8 kg	1/2 of 6.8 kg

Table 2-2. Molecules Observed in Comets
(July, 1972, C. Arpigny)

Gas	Molecular Weight
H	1
CH	13
CH ⁺	13
CH ₂	14
NH	15
NH ₂	16
OH	17
OH ⁺	17
Na	23
C ₂	24
CN	26
CO ⁺	28
N ₂	28
C ₃	36
CO ₂	44

temperature interstellar material, but this possibility is certainly an attractive one and would provide a straightforward explanation for the presence of such complexes as C₂ and C₃ in cometary spectra.

In addition to the observed neutral and ionized gases, there may be appreciable amounts of He, Ne, and Ar associated with any comet, but especially with "new" ones. These inert gases can be identified in mass spectra with little difficulty and their isotopic ratios readily determined. The isotopic

Table 2-3. Molecules Observed in the Interstellar Medium
(March, 1973, P. Solomon)

H ₂	NH ₃
CH, CH ⁺	H ₂ CO
CN	H ₂ CS
OH	HNCO
CO	HCOOH
CS	HC ₃ N
SiO	CH ₃ OH
H ₂ O	CH ₃ CN
HCN	NH ₂ HCO
H ₂ S	CH ₃ C ₂ H
COS	CH ₃ HCO
	CH ₂ NH

ratios of the inert gases vary greatly in nature, depending on the source of the gas. For example, of the neon present in the earth's atmosphere, neon-20 is by far the most abundant isotope and even neon-22 is far more abundant than neon-21. In neon that has been produced by nuclear spallation through cosmic ray bombardment, as in some meteorites, all three isotopes of neon are nearly equally abundant. Helium-4 can accumulate through long-lived radioactive decay; the abundance of argon-40 is similarly augmented. Because isotopic variations can arise in various ways in the inert gases, their measurement may provide significant clues to the nature and origin of comets.

Taken at face value, this line of reasoning suggests that a mass spectrometer sent to explore the gases in the immediate vicinity of the nucleus of a comet should have a mass range of about 1 to 100 amu in order to accommodate even more complex and heavier molecules than those in Table 3

(we have every expectation that this listing is very incomplete). The dynamic range should be adequate to handle densities from a few tens of molecules cm^{-3} to about 10^7 molecules cm^{-3} . Ideally, it should be capable of examining both ionized and neutral species, but in practice it may prove necessary to fly two instruments. Design considerations for such instruments have been developed in previous NASA reports and the following discussion is adapted from these documents (primarily Nier and Hayes (1971) in the Yerkes study).

The principal problem in mass spectrometric measurements is obtaining high enough counting rates to detect rare species and to provide adequate spatial resolution. Preliminary calculations have been done based on a typical fast flyby velocity of 10 km/s with a miss distance of 10^3 km. If it is possible to obtain velocities of only 4 km/s as proposed for the Encke slow flyby mission, one can obviously do better. On a first estimate basis it would appear that six mass spectra can be obtained.

Of these six spectra, two are of the inner coma, each using an integration of half of the 1900 seconds when the probe is within 5×10^3 km of the nucleus. Two spectra are of the intermediate coma (3×10^3 km - 3×10^4 km) one entering and one leaving with an integration time of 3000 seconds and two spectra are of the outer coma ($>3 \times 10^4$ km) with an integration time of 10,000 secs.

For the three regions of the coma the average density of particles (ions, molecules and radicals) is assumed to be $5 \times 10^6 \text{ cm}^{-3}$ (inner), $5 \times 10^4 \text{ cm}^{-3}$ (intermediate) and $5 \times 10^3 \text{ cm}^{-3}$ (outer) and the total number of ions, of all species, counted in a collision-free mass spectrometer will be 5×10^7 , 1.5×10^6 and 5×10^5 ions respectively. Note that collisions become unimportant at slow enough speeds. Of the totals, parent molecules may be expected to represent 1% or less of the inner coma but a negligible fraction of the rest of the coma. These counting rates are adequate for reasonable spectral resolution (although some molecules may be unobserved) but provide marginal spatial resolution.

Another problem that must be confronted is the overlapping of different molecules at the same nominal mass number which could lead to confusing mass spectra (e.g., CO and N_2 at $M = 28$, NH_2 and CH_4 at $M = 16$; NH and CH_3 at $M = 15$, etc.). This problem arises since normally unstable molecules

resulting from photodissociation are likely to be quite abundant in a cometary atmosphere; their mean free paths will be very long and the probability for recombination of these molecules upon collision with other molecules or surfaces will be extremely minute. A highly calibrated mass spectrometer operating with variable ionizing electron energies will be required to circumvent the major portion of this problem. In addition, spectra will have to be taken in both the ionizing and non-ionizing modes.

The major difficulty for the application of the mass spectrometer experiment is the proper acquisition of cometary gases. A high relative velocity of the cometary molecules with respect to the spacecraft presents a sampling problem as yet unsolved. One possible sampling technique would be to use a velocity filter tuned to the mean intercept velocity with the comet and oriented along the cometary velocity vector. The ion source would be located at the entrance to the velocity filter. Coincidence gating of the velocity filter electric potential and the ion detector could be utilized to discriminate between cometary species and background gases.

Several additional methods for operating the mass spectrometer were considered in the Yerkes study with a view toward identifying the most sensitive mode. The conclusions were as follows:

- (a) Use of a complete stagnation chamber - would probably lose most radicals but has very high sensitivity for stable gases.
- (b) Total collection in a cooled chamber with subsequent analysis - requires valves and could get complicated. Unable to measure radicals and has little advantage over (a) above.
- (c) Semi-open chamber - can probably see some radicals and get semi-quantitative abundances and a good measure of stable molecules.
- (d) Fly through (collision free) - good for all species but not as sensitive as those above. To prevent collisions the aperture would need careful orientation unless the flyby speeds were slow enough.

These and other techniques should be carefully reviewed by experimenters in order to obtain the maximum scientific yield from the instrument. Simple confirmation of the existence of radicals already known to be present would be a very disappointing result, although even in this case one could expect to gain increased information on the spatial distribution of these various species. It is perhaps worth stressing explicitly the benefits that this experiment will gain from decreased fly-by velocity and a minimum miss distance: the former permits longer integration times or more samplings, while the latter greatly increases the chances of actually detecting the parent molecules.

2.2.2 UV Spectrometry

Like the mass spectrometer, a UV spectrometer is an excellent survey instrument, well-suited to an exploratory mission whose purpose is to search for new molecular and atomic species, while confirming previous identifications and interpretations. A basic constraint on the design of such an instrument is that it should overlap with the region of the spectrum accessible from the ground ($\lambda > 3000\text{\AA}$). A further consideration that must be borne in mind is that there will be rather large numbers of UV observations of comets if the first mission is delayed until 1980. The results obtained from these studies (by the OAO's, the OSO's, rockets, the IUE, etc.) must be critically evaluated at the time a UV experiment is picked for inclusion as a mission experiment. The higher spatial resolution and greater intensity (in some cases) that one may expect a priori from putting the instrument on the spacecraft must be compared with the higher spectral resolution probably achieved by some of these other techniques.

The objectives of a satisfactory UV experiment were well expressed in the Yerkes report and are reproduced below:

- (a) Identification of neutral and ionic species
- (b) Determination of the extent of the coma constituents as a function of heliocentric distance during approach and departure
- (c) Determination of the coma constituents as a function of distance from the nucleus

- (d) Definition, with high resolution of the morphological structure of the coma in terms of its constituents
- (e) Determination of the size and spatial distribution of dust in the coma and tail.

Spectrophotometric measurements of coma and tail do not require a close approach to the comet. A miss distance of 10^4 km still affords a resolution of about 180 km for a typical instrument. Constraints on the speed at which one flies past the comet are also relaxed compared with some of the other instruments, although one obviously increases the viewing time as the approach velocity is reduced.

The situation becomes rather different, however, if one intends to use this instrument to characterize the gases in the immediate vicinity of the nucleus, i. e., to search for the elusive parent molecules. In this case, one again wishes a close, slow fly-by, and the proposed 4 km/sec Encke slow flyby becomes very attractive. At a miss distance of 1000 km \pm 500 km, the candidate system referred to above would be able to resolve the inner coma to a diameter of 10 km, which should be more than adequate since the parent molecules should still be present in undissociated form within this distance from the nucleus.

Some sample instruments suggested in the Yerkes report are described below:

a) Filter Photometer. A simple filter photometer using refracting (or for Lyman α , reflecting) optics consisting of some 10 channels can be constructed for about 2 kg and will consume approximately 1 watt. A range of flight units of this type are available from which to choose. Bandpasses could include Lyman α , OH, CN, C_2 , continuum, C_3 , N_2^+ and other selected lines. By incorporating the instrument on a scan platform or on a spinning spacecraft, crude images of the comet could be constructed for each constituent. This is a low data rate experiment.

b) UV Spectrometer. A reflecting grating instrument will give high spectral resolution over a continuous spectral region. Such a dispersive

instrument is more efficient than a filter, particularly if well defined bands are specified. Instruments with channeltron detectors would be suitable and would have a weight of approximately 5 kg.

A UV spectrometer which covers the spectral range from 1100 to 3400 Å includes the important Lyman alpha region (1216 Å), and hence would be valuable for detection of a hydrogen halo. This range also includes bands of OH, NH, C₂ and CN, known to be present in cometary spectra. A very important consideration is that the instrument cover a wavelength range largely inaccessible from the surface of the earth but blend into a range that is accessible. Thus, it would be capable of finding as yet undiscovered species and would give data which would serve as an excellent complement to data obtained from simultaneous earth-based observations.

c) Imaging Spectrometer. The use of an image tube (vidicon type) in combination with a filter wheel would allow pictures of the whole coma to be taken at specific wavelengths corresponding to the constituents. The intensity distribution, even if not photometrically absolute, could be used to define the morphology of the coma. Such images could be obtained sequentially from the time of acquisition, with the largest halo viewed first (CN) until it fills the field of view, and then switching the filter to the next species, and so on. Further study would be required of the intensity levels, exposure times and photometric accuracy to verify this as a comet experiment. If feasible, it would represent a very large enhancement of a simple imaging experiment.

2.2.3 IR Spectrometry

An IR spectrometer experiment poses particular challenges. It would address two important objectives: the identification of parent molecules and surface composition. However, there are currently no existing or feasible spacecraft instruments which would be capable of detecting and measuring the amounts of species such as H₂O, NH₃, CH₄ and CO₂ which are likely to be present. This applies to both emission and absorption spectroscopy, the latter by viewing the Sun through the coma. A simple calculation, based on a recent model of comet Encke (Ref. 5. Taylor, 1973).

It indicates that the maximum path length of H_2O along a typical viewing line might be of the order of 10^{-2} cm atm. This is two orders of magnitude below the detection limit of existing instruments operating under more favorable conditions. The situation is worse for the other species which are probably at least an order of magnitude less abundant than H_2O .

For spectroscopy of surfaces, it is highly desirable that an instrument be able to resolve the nucleus. This requires a narrow field of view, which appears to be impractically small for the attainment of reasonable signal to noise ratios, even if cooled detectors are used. For spectroscopy of the icy halo, however, spatial resolution is of secondary importance and this objective should be feasible from Earth orbit.

2.3 DENSITY EXPERIMENTS

Densities of asteroids and comets is a key parameter for which virtually no information is available. The density of cometary nuclei as inferred from the previously mentioned meteoritic theories is probably low.

Table 2-4 shows a great drop in density between the inner and outer planets, and the asteroid belt occupies the area between Mars (density 3.97) and Jupiter (density 1.334). Thus, the asteroids occupy a portion of the solar system where a major change in density occurs.

Currently, asteroid density determinations depend on mass determinations derived from observations of orbital perturbations during mutual close approaches (Hertz, 1968; Schubart, 1971). Volume is determined from diameter determinations. These are based on telescopic resolution of the disc (Dollfus, 1971) or on the use of infrared measurements to estimate albedo, and through this convert brightness to diameter (Allen, 1971; Chapman and Morrison, 1973). Densities estimated range from about 1.6 to 5 g cm^{-3} , with uncertainties in the values ranging from $\pm 60\%$, upward. These densities are similar to those of meteorites; if they were known accurately one could use them to associate the asteroids with specific meteorite types.

Spectral reflectivity data (Chapman et al., 1971) indicate that pyroxene is present on the surface of Vesta with an overall spectrum similar to basaltic

Table 2-4. Densities of Planets, Satellites, and Selected Meteorites

Planet	$\rho(\text{g cm}^{-3})$	Satellites	$\rho(\text{g cm}^{-3})$
Mercury	5.4		
Venus	5.1		
Earth	5.52	moon	3.34
Mars	3.97	Phobos-Deimos	unknown
Jupiter	1.334	Galilean	1.71 (Callisto), -3.73 (Io)
Saturn	0.684		~0.5 (Mimas), -2.42 (Titan)
Uranus	1.60	Miranda-Oberon	unknown
Neptune	unknown	Triton	~4.0
Pluto	unknown	unknown	unknown
Meteorite Class			
Enstatite (E) chondrites			3.4 - 3.8
Olivine-bronzite (H) chondrites			3.4 - 3.8
Olivine-hypersthene (L) chondrites			3.3 - 3.6
Carbonaceous-I (C1) chondrites			~2.2
Carbonaceous-II (C2) chondrites			2.5 - 2.9
Carbonaceous-III (C3) chondrites			3.4 - 3.5
Iron meteorites			7.9

achondrite meteorites. If the larger asteroids do indeed have densities of about 5, they would be interesting considering that no planetary satellite has such a great density.

No Apollo or Amor asteroid has even an estimated density, primarily because they are too small. Some of the Earth and Mars crossing asteroids,

such as Icarus, could be extinct comets. If so, these asteroids may have densities of about 2 (see Table 2-4), similar to C1 chondrites.

Accurate estimates of the density of comets and asteroids require space missions. The techniques that might be used for density measurements are the previously noted doppler-tracking method, the gravity gradiometer, and the inferences from in-situ observations of the nucleus.

2.3.1 Doppler Tracking

When applicable, doppler tracking, which has been reviewed by Anderson (Ref. 6) is the preferred method of estimating density because no added weight for an experiment package is needed and density can therefore be obtained "free". The technique is probably not applicable to asteroids smaller than 50 km in diameter even on a slow (5 km/s) flyby. Thus, the problem with doppler tracking is that it is useful only for the largest asteroids, and probably not to comets at all.

2.3.2 Gravity Gradiometer

Although it has not been proven in flight, the gravity gradiometer (Ref. 7, Forward, 1971), shows great promise in the determination of densities of comets and asteroids on slow flybys. Gravity gradient instruments work on the principle of measuring differential tensions, compressions, or torques induced in the sensor by the gradient of the gravity force field. Spin stabilized spacecraft are preferred so that the gravity field of the spacecraft cancels. At 1 km/s, the gravity gradiometer is applicable to comets and asteroids (those with diameters >1 km), but for even 10% accuracy, the flyby altitude must be less than twice the radius of the asteroid. Thus, the instrument will only provide useful data on a very slow flyby, rendezvous, or landing mission. Since early missions which encounter asteroids enroute to comets will have encounter velocities of 8-15 km/s or greater, gravity gradiometers will not be applicable.

2.4 DUST PARTICLE STUDIES

On a comet or asteroid mission we clearly need a device which yields particle size and flux data; this should also yield trajectory parameters if possible. On an early cometary mission this may be the main type of dust-particle information obtained, unless very rapid developments in the dust-particle analysis field occur in the next few years.

2.4.1 Mass, Velocity, and Orbital Parameters

A special problem is the high particle fluxes which may exist near a comet. One possibility for obtaining data is an impact ionization detector, typified by the instrument currently flying on the HEOS 2 satellite in eccentric polar orbit about the earth (Ref. 8. Dietzel, et al., 1973). This device measures the amount of positive and negative charge in a plasma produced by particle impact on a refractory metal (tungsten or gold), as well as the rate of expansion of the plasma cloud. These parameters provide the mass and velocity of the impacting particle. Because of the limited solid angle of acceptance ($\sim 76^\circ$), rough trajectory information is also obtained. Impacts at velocities below approximately 3 km/s yield too little ionization to allow accurate measurements. The maximum impact rate is about 10^4 sec^{-1} , and would probably be telemetry-limited rather than instrument-limited near a comet.

Pioneers 10 and 11 carry an instrument known as Sisyphus which consists of four telescopes with parallel axes (Ref. 9, Grenda, et. al., 1970).

The sisyphus detection system uses solar radiation reflected or scattered from the particle for detection and size and velocity determination. The passage of the particle is measured by at least three independent nonimaging optical subsystems. The entrance and exit time of the particle through each of the fields of view is all that is required to completely determine the range and three velocity components of the particle. From the measured range and the separately measured amplitude of the signal, an "albedo cross section" equal to the reflectivity times the illuminated cross-sectional area is determined.

When an object with a/R (a = range of object from spacecraft, R = radius of object) ratio greater than the detection limit passes through the viewing cones subtended by any three of the telescopes, a , R and orbital parameters can be determined. If only two telescopes view the object, only a and R can be determined, and if but one telescope sees the object, only the a/R ratio can be determined (the reflectivity of the object must be assumed in all cases). The a/R detection limit for a dark (stars only) sky at 1 AU from the sun is about 10^{-5} (a 1 mm particle is detectable at 100m, a 10 km object at 10^6 km, etc.). The Pioneer spacecraft are spin-stabilized, but Sisyphus can also function on a three-axis stabilized spacecraft. In fact another version is scheduled to fly on the Mariner-Jupiter Saturn.

Although Sisyphus has a dynamic range of 10^6 viewing against an average stellar background, it is less versatile against a radiant coma background. The range to radius ratio of 10^6 (an albedo of 0.2) may be reduced two orders of magnitude during an approach from the sun side of a comet (Ref. 10. Newburn, et al, 1973).

In summary, the Sisyphus detector appears to be well suited for measuring dust particles at great distances from the comet, and, by means of orbital parameter information, distinguishing random particles from comet-associated particles. Near the comet (where orbital information is inherently less valuable) the Sisyphus appears much less useful. For these close range measurements an impact counter (such as the impact ionization detector) offers better ability to respond to the high particle fluxes if speed is sufficiently high, (i.e. >3 km/s).

An alternative dust experiment was used on Pioneers 8 and 9. It measures the flux density, kinetic energy, momentum, speed, and direction of particles of energy ≥ 0.2 erg. From these data, the mass may be deduced. However, solid particle experiments have in the past given controversial results. For this reason, different types of dust detectors may have to be used together in complementary fashion.

2.4.2 Chemical Composition

The only way to determine the composition of the dust ejecta of a comet from a fly-by mission appears to be an impact ionization mass spectrometer.

Unfortunately, current impact instruments are too primitive to be well suited for a comet mission, and much more developmental work is needed. The problems are of two basic sorts: 1) The current generation of instruments begins to yield compositional information only at encounter velocities above 10 km/s; below this limit the velocity and mass of a particle are determined, but too few elements become ionized to yield useful compositional data. 2) The resolution ($M/\Delta M$) of the Helios instrument (Ref. 8) (which utilizes a time-of-flight mass spectrometer) is about 5 at low masses, increasing to 10 at higher masses. As a result, the instrument cannot distinguish between Mg, Al and Si, between K and Ca, and between Fe and Ni. Needless to say, isotopic ratios, which would provide elemental "signatures" if available, are also not obtainable.

2.5 FIELDS AND PARTICLES

To the many scientists interested in plasma physics, comets offer fascinating challenge and an unique opportunity.

The experiments which make up a fields and particles group of instruments will address both the quantitative and qualitative understanding of solar wind interaction, tail formation and coma formation. Data from these instruments may possibly be applicable to other areas as well, for instance, structure and properties of the nucleus inferred from magnetic properties. The fields and particles package can be expected to produce definitive experimental results in several areas of plasma physics related to coma and solar wind interaction phenomena.

Table 2-5 summarizes, in general, fields and particle experiments.

2.5.1 Plasma Analysis

Protons and α particles are the principal ionic constituents involved in the solar wind-comet interaction and in the cometary tail. It is valuable to make relatively high time resolution measurement of these constituents (≥ 1 measurement/minute) in the thermal energy range with sufficient energy resolution to determine velocity, density and temperature to $\sim 10\%$, 20% , and 30% respectively. At least two components of the velocity must be determined.

Table 2-5. Fields and Particles

Instrument	Experiment	Significance
Plasma analyzer	Determine the distribution functions of the thermal protons and α particles in tail and near the coma.	Determine and understand the nature of the solar wind-comet interaction and the flow field.
Magnetometer	Measure the magnetic field in and near the comet.	Possible remnant magnetism of nucleus; solar wind-comet interaction; tail structure, basic physics of magnetized plasma - neutral gas interaction.
Electron analyzer	Measure 3-D distribution function of electrons ≤ 5 eV to ± 10 KeV.	Determine role of electrons as an ionizing agent; solar wind-comet interaction; heat transport in cometary plasma.

A typical plasma experiment might include three detectors:

- (a) An electrostatic analyzer, mounted in a manner to study ions and electrons in the hemisphere centered about the solar direction. It would cover ions from 80-8000 eV and electrons from 4-400 eV.
- (b) Small electrostatic analyzers to extend the electron observations at energies up to 1 keV into the other hemisphere, and search for electrons accelerated by several possible mechanisms at encounter.

- (c) A final pair of electrostatic analyzers of very high sensitivity and extended range to study the tails of the plasma velocity distribution functions of both ions and electrons up to 50,000 eV.

Electrons may be the primary ionizing agent in the coma and they probably carry most of the thermal energy in the cometary plasma. To study these processes, it is necessary to measure the three dimensional distribution function of electrons with energies ranging between at least 5 eV and 10 keV. Lower energy measurements would be desirable for the thermal studies and higher energy measurements would be desirable for the ionization studies, but this requires new developments.

Also included for plasma analysis might be a very low frequency (VLF) electric and magnetic wave experiment for studying the solar wind interaction with the comet. Hopefully, the experiment would provide signatures for the various interaction possibilities leading to identification of the interaction type, and to detailed physical understanding of the macroscopic processes that govern the interaction.

The sensors would include a single-axis search coil for magnetic measurements and a single-axis electric dipole for electric measurements, placed on a common boom. The magnetic measurements cover frequencies up to 2 kHz and the electrical measurements up to 200 kHz.

2.5.2 Magnetometry

It is essential to understand the role magnetic fields play in the interaction of the solar wind plasma with the neutral gases of the coma and their influence on the structure and motions of material in the tail. One must also consider the possibility that the nucleus has a weak magnetic field of its own.

The measurement of weak magnetic fields ($<10^{-100}\gamma$) requires a "magnetically clean" spacecraft or other approaches to provide sufficiently accurate data. Instruments with the necessary accuracy and sensitivity have been flown on various spacecraft, among them IMP's, Pioneers, OGO's, and Mariners.

SECTION III

INSTRUMENTS OF POTENTIAL APPLICABILITY

3.1 RADIOMETRIC AGE DETERMINATION

There are only a handful of terrestrial laboratories producing age measurements of uniform trustworthiness. Results obtained in a poorly controllable remote mode would likely be of much lower quality, and provide little in the way of constraints on rival theories. The one technique potentially applicable to remote analysis is potassium-argon dating. However, studies of lunar soils have revealed an unexpected complication; viz., excess argon resulting from reimplantation. All in all, it appears preferable to delay age determination experiments until returned cometary and asteroid samples are available.

3.2 X-RAY DIFFRACTION INSTRUMENTATION

Crystal structures formed in a specific environment record a great deal of information about this environment. Among techniques of this sort only x-ray diffraction appears to be a practical candidate for landing missions. Visible and infrared polarization measurements which potentially could yield such information are rendered less effective by shock and radiation-induced opacity and the complex variety of sources of such polarization (Ref. 11. Arrhenius, et al., 1973). Visible and IR absorption measurements are satisfactory for remote mineralogical surveys, but their sensitivity does not improve significantly upon landing, and they are not suitable for such missions.

Diffraction instrumentation is not flight-ready, but aspects of such instruments have been investigated by several authors (Ref. 11). Because of the inherent difficulties, only relatively high phase concentrations can be measured; in most cases only phases with abundances greater than about 10% (olivine, pyroxene, possibly plagioclase) could be identified, although the high symmetry and inherent resistance to disordering processes suggests somewhat better sensitivity for metals and sulfides. Such measurements could serve to aid in target selection for sample return missions, and the development of diffraction instrumentation should be initiated.

3.3 GAMMA-RAY SPECTROMETRY (REMOTE ANALYSIS)

Remote gamma-ray spectrometry allows the determination in comet or asteroid surfaces of the concentrations of long-lived natural radioactivities (potassium, uranium, thorium) and the estimation of the concentration of a group of light elements (e.g., sodium, aluminum, manganese) from the determination of short-lived radioisotopes induced by cosmic ray interactions. This instrument is on lunar orbiting satellites and is yielding important concentration data (Ref. 12. Metzger, et al., 1972). This technique should work well on rendezvous or landing missions; it cannot be expected to yield suitable data on flyby missions with velocities > 4 km/sec and miss distances > 1000 km. Given a sensitive enough instrument, it may be able to detect abundant radio-nuclides in the sufficiently dense parts of the cometary coma during rendezvous.

Of special importance for comet missions is the possibility this technique offers for detection of hydrogen, which should be present as ice and hydrated silicates and hydrides of carbon and nitrogen. Hydrogen is detected via the 2.3-MeV resonance emission line following neutron capture. The detection limit for water on a landing or rendezvous mission is estimated at about 5 - 10%; thus it could also be determined on asteroids similar in composition to C1 or C2 chondrites.

Although gamma-ray spectrometers are already quite sophisticated and flight-proven, continued development is needed to insure that state-of-the-art instruments are available for the first rendezvous missions.

3.4 X-RAY FLUORESCENCE SPECTROMETER (REMOTE ANALYSIS)

This technique relies on the excitation of atoms by solar corpuscular and electromagnetic radiation. In lunar orbiters it has been demonstrated to be a very useful method for remote analysis (Ref. 13. Adler, et al., 1972).

Limitations of the method are that only major elements can be detected, and the particularly simple K-spectra are excited efficiently by the sun only up to about 2 keV. The range is thus essentially limited to magnesium, aluminum, silicon, oxygen and carbon if in sufficiently high, but unlikely, concentrations of about 10%. The more complex L spectra of heavier elements (such as iron

and nickel) may be detectable by taking advantage of further improvements in the detector design.

Measurement of composition by x-ray fluorescence, utilizing units of the kind used on Apollos 15 and 16, are not usable in flyby missions (encounter velocities ≥ 5 km/sec), but will be most useful in rendezvous missions, where the asteroid will be close enough to generate an acceptable signal.

It will also be useful for the study of cometary surfaces during rendezvous, and possibly for the comas of relatively active comets.

3.5 X-RAY FLUORESCENCE AND α -PARTICLE SCATTERING SPECTROMETERS (LANDING MISSIONS)

The α -particle scattering method relies on the differing energies of particles undergoing 180° scattering; the heavier the atom, the greater the backscattered energy. This technique has been developed to a high degree by Turkevich and collaborators (Ref. 14. Turkevich, 1971). The technique in its present form permits analysis of the eight most abundant elements found in the lunar crust (70.3%).

The use of x-ray fluorescence for remote analysis was described above. The principles are the same on a landing mission, except that excitation is by a source carried with the instrument. An instrument using radioactive isotopes as excitation sources is part of the Viking-Mars landing spacecraft in 1975.

The sensitivity of the x-ray fluorescence instrument is somewhat better than that of α -particle spectrometry. The practical range can be extended relatively easily to the order of 0.03 atom % as compared to 0.3 atom % for α -scattering. Instrument development should be continued in order to take advantage of better detectors now becoming available.

SECTION IV

MISSION CLASSES AND SIGNIFICANT PARAMETERS

Spacecraft investigations to comets and asteroids can be accomplished with a variety of spacecraft, and experiment repertoires. This report classifies missions and identifies significant parameters along lines similar to those employed in earlier reports. The three classes of missions are:

4.1 FLY-BYS OR INTERCEPTS

These are most likely to be implemented during the next decade and represent the first logical step in studies of the minor bodies.

Fast fly-by missions are those with relative speeds greater than 5 km/s (Yerkes Report and 1972 Report of Comet and Asteroid Mission Study Panel).

Slow fly-by missions are those whose intercept speeds are less than 5 km/s. (Ibid.)

These missions offer the best opportunity for early studies of comets and asteroids. A number of critical parameters are significant in evaluating the relative merits of different missions and instrumentation for specific problem investigations. These critical parameters are:

- (a) Miss Distance, or closest distance of approach of the spacecraft to the target
- (b) Relative Velocity vector, both the magnitude and direction of the relative motion of the spacecraft and target
- (c) Relative Heliocentric Positions and Distances of the intercept point and earth, especially the communication distance and the angular elongation and distance of the intercept point from the sun.

Various experiments are influenced differently by the above critical parameters. A sufficiently small miss distance is essential for all experiments requiring direct observations of the solar wind interaction region with the cometary atmosphere, or the coma itself. The relative velocity vector is important for approach viewing conditions and for determining the distortion

of the measured characteristics due to a "doppler" effect. It is also important in assessing impact hazards. Of special importance for measuring chemical composition and other characteristics is the possibility that a high relative velocity leads to chemical reactions on surfaces of the spacecraft and detectors, leading to confusing results reflecting the dynamics of such interaction more than the nature of the external medium.

If the relative velocity is 1 to 5 km/sec and the passage not too distant, it becomes feasible to get infrared data on a small body, to detect x-rays from accelerated plasma electrons (if any), and to detect γ -rays from decay of natural and induced radioactivity in the outer crust of the body.

Miss distance, relative velocity and mode of spacecraft stabilization combine in importance in imaging experiments because of the convolved effect of the instrument aperture, scan rate, response rate, data rate and other factors relative to reconstruction of effective images from the raw data.

Lastly, the relative heliocentric positions of the intercept point and earth are important in determining the communications capability for the specific mission, the earth viewing characteristics, the thermal environment of the encounter, and the solar wind and insolation incident on the target body. Intercepts occurring near superior conjunction are obviously not attractive because of solar interference on radio telemetry systems.

Miss distances greater than 100,000 kilometers for probably most comets and all asteroids preclude any direct observations of the cometary atmosphere and interaction regions and certainly make a poor basis for imaging or indirect emission type observations. Miss distances less than 10,000 kilometers are required, and generally speaking values less than 1,000 kilometers are essential for adequate studies of the compositional variation and structure of the cometary coma, and solar wind interaction region. For certain indirect observations of the asteroids, miss distances must be less than 100 kilometers in order that the effect and influences of the asteroids are sensibly measurable above background levels.

A set of possible fly-by experiments, taken from the study panel's 1972 report, is presented as Table 4-1. Note that interplanetary experiments related to cosmic rays are not listed, but can be flown on an early survey mission at small additional cost in weight and data rate.

Table 4-1. Possible Experiments for a Flyby to
Comets and Asteroids

Instrument	Experiment	Significance
Imager	Mapping surface.	Determine shape and surface features of asteroid and opacity of comet.
Tracking Data Analysis	Determine the influence of gravitational field on trajectory.	Determine mass and, in conjunction with imaging, density.
Magnetometer	Determine magnetic field and variations.	Magnetic field associated with asteroid and its interaction with the solar wind. Nature of cometary tail.
Plasma Probe	Determine nature of plasma.	Nature of plasma in vicinity of asteroids and in comet tail.
Impact Ionization Counter	Determine particle distribution.	Examine distribution of particles in vicinity of comets and asteroids.
Mass Spectrometer	Collect and analyze particles.	Determine chemical composition of cometary material.
Photopolarimeter	Determine brightness, colors, and polarization over a wide range of phase angles.	Determine surface texture and composition of asteroids and particle characteristics of comets.

The experiments of Table 4-1 gain from increased time resolution. The error in a mass determination from doppler tracking goes down as the $3/2$ power of the relative velocity. Table 4-2 gives a set of instruments to be considered for a slow flyby mission as well as a rendezvous.

Table 4-2. Slow Flyby - Rendezvous Comets and Asteroids

Instrument	Experiment	Significance
X-ray spectrometer	Determine Al/Si and Mg/Si ratio and perhaps others using solar energy as a source.	Major parameter in determining bulk chemistry of body.
Gamma-ray spectrometer	Determine distribution of U, Th, K, and others.	Important to characterize chemistry, differentiation and heat sources.
High resolution imager	Sample surface features in detail.	Look for detailed surface appearance and reconnoiter for a landing.
Photometer and polarimeter	Determine spectral reflectance in optical and near IR, polarization phase curve.	Determine, if possible, a few features of bulk mineralogy such as iron distribution and particle size distribution.
Electromagnetic sounders	Determine reflection as function of frequency from a few MHz to a few hundred MHz.	Give dielectric constant surface scattering and subsurface layering in upper few 100 meters.
Laser altimeter	Examine roughness of surface and shape of body.	Impact history of the body.
Magnetometer	Measure magnetic field due to body (to about 0.1 gamma).	Establish level of any paleofield frozen into the rocks as well as solar wind character.
Tracking data Analysis	Determine mass by disturbance of trajectory.	Knowing size of body, this will give a measure of the density, of fundamental importance to the nature of asteroids.
Gravity gradiometer	Determine mass distributions of asteroid and mass of cometary nucleus.	Map gross heterogeneity in mass distribution of asteroids.
UV Spectrometer		Examine cometary atmospheres.
Mass spectrometer	Analyze gas material.	Analyze cometary atmosphere.
Plasma probe		Nature of ionized material in cometary atmosphere.
Nucleus probe with imager		Determine properties of cometary nucleus.

4.2 RENDEZVOUS

The rendezvous mission permits the most sophisticated in-situ analyses of the chemical and physical characteristics of comets and asteroids. The progression to the rendezvous mode should make it possible to solve some of the most central problems associated with these bodies. In fact, the eventual resolution of certain problems, especially those associated with the nuclei of comets and the characteristics of asteroids, require the conduct of such missions in an orderly sequence of spacecraft investigations.

Velocities below 1 km/s significantly improve the environment for the previously discussed gravity gradiometer experiment, given that the range is less than twice the radius of the body (see Section 2.3.2).

A nucleus or surface probe becomes possible at an approach velocity of a few meters per second, enhancing the chances for docking and anchoring. On the surface, major elements could be probed by backscatter of α -particles, x-ray fluorescence, neutron capture accompanied by γ -ray analysis, a seismometer and mass spectroscopy of plasma from a laser pulse. If the anchor is a penetrating boom, a temperature gradient measurement would be important. An accelerometer and strain gauge should record the impact. Microscopic imaging by holography using rotating linear polarization of the reference beam may reveal the structure and proportion of opaque, birefringent, and isotropic phases present in the surface layer.

The dust particle experiments that require high relative velocities may be omitted on a rendezvous mission. Other experiments described in the previous sections are generally significantly enriched by rendezvous. New sensitive laser absorption techniques might be considered, because of simplicity, as a replacement of mass spectroscopy for analysis of asymmetric molecules. Table 4-2 includes instruments to be considered for a rendezvous mission.

In dockings or soft landings, remote sample analysis might be made and resultant data telemetered back to earth. Properties such as surface texture, magnetic field, chemical composition, crystal structure and radioactivity could be studied in detail yielding important information on the origin and evolution of the solar system. The recent exploration of the lunar surface should guide us in planning for rendezvous and docking or landings the asteroids and comets. For soft landings, Table 4-3 lists some possible experiments.

Table 4-3. Soft Landing

Instrument	Experiment	Significance
Surface imaging	High-resolution imaging in visible and infrared light.	Study craters, faulting, collapse features, color, albedo, etc.
Penetrometer	Determine mechanical Nature of near surface material; xerographic study of cohesion.	Is the surface hard or covered by regolith and soil?
Chemical analysis	α -particle spectrometer, X-ray sensing, γ -ray spectrometry.	Determine bulk chemistry of surface.
Atmospheric composition (mass spectrometer, etc.)	Study gas emitted perhaps after penetration.	Determine composition of trapped gas.
Heat flow	Measure thermal gradient and thermal conductivity probably during a 90-day mission.	Measure of thermal balance at surface and if it is a good insulator get some measure of internal heat generation.
Seismometer (active and passive)	Listen for impacts due to meteorites and determine depth characteristics using active part with a mortar, complete experiment possible in a 90-day mission.	Nature of impacts and determination of internal structure and gas release.
Magnetometer	Measure steady D. C. field and variations associated with solar wind (record field for 90 days).	Measurement of paleofields and study of plasma properties over a period of time.
Plasma probe	Measure density and time fluctuation of plasma.	Correlation with magnetic variation data.

4.3 EARTH-BASED STUDIES: GROUND SUPPORT, ORBITERS, AND ROCKETS

These represent already existing methodologies developed from space technology which can be (and in some limited circumstances have been) applied to studies of comets.

4.3.1 Ground-Based Support

4.3.1.1 Comets

Until recently nearly all cometary information was obtained by ground-based observations and our basic physical picture of comets results from our interpretation of the ground-based data. The importance of continuing these observations as an integral part of a complete program of cometary research seems self-evident. Information obtainable from the ground should not be gathered by space experiments. A ground-based observing program requires observations with a variety of instrumentation through telescopes of different apertures and fields; examples are given below.

a. Photography - The structure, evolution, and dynamics of comets can be studied through white light, color, and filter sequences of photographs. Telescopes with a large scale are needed to obtain observations of the nuclear region and its fine-scale structure. Observations with large angular field are needed to determine the over-all structure including facets of the comet's interaction with the solar wind, such as the orientation of the comet tails.

b. Photometry/Polarimetry - These observations provide information on the total amount of gas and dust in the comet and their density variations. Estimates of the size distribution of the dust particles can also be obtained. These observations are carried out both in wide-band or narrow-band filters and can refer to a resolved portion of the comet or essentially to the whole comet. The choice depends on the specific problem at hand. For instance, for the comparison with theory of scattering by small particles (the Mie theory), the filters have to be carefully selected to exclude emission lines.

c. Spectroscopy - The composition and physical state of the cometary atmosphere can be studied with spectra of the constituent molecules and atoms. The time (and heliocentric distance) variations of the emissions of specific substances is of particular interest in the study of the production of the cometary atmosphere. These changes are due to the gradient in solar light (and possibly solar-wind) energy on the nuclear ices, but few details are known.

4.3.1.2 Asteroids

The key ground-based observations in support of an asteroid space mission are 1) those which lead to more accurate orbital parameters; and 2) those which provide more detailed information about the physical and chemical properties of potential targets.

Table 4-4 shows a comparison of different types of ground-based studies of asteroids, together with estimates of required amounts of time at the telescope and for preparations and data reductions.

Discovery and identification of new asteroids are presently pursued with small telescopes at observatories abroad (for instance at Nice), with the small Schmidt at Palomar (the Shoemaker-Helin Search), and occasionally with the big Schmidt at Palomar (for instance, the Palomar-Leiden Survey). Observations for orbit determination are made both abroad and, for faint objects, in Arizona by Roemer and at the Harvard 1.5-meter reflector by McCrosky, et al. This work should continue to receive assignment of telescope time and research grants.

A search should be made for asteroid candidates (in addition to Ceres and Vesta (Schubart 1971)), for use in mass determination. This time-consuming work is strongly encouraged because of the fundamental importance of density, which is, of course, obtained from mass and size.

Size determination through interferometry is a new technique. Further development, and application to asteroids, is urgent. Indirect size determination through infrared photometry and phase-dependence polarimetry (and absolute photometry) is actively pursued, at the universities of Hawaii and Arizona, respectively.

Table 4-4. Comparison of Ground-based Observations

Type of Observation	Physical Parameter	Telescope Time ^a	Preparations reductions, Manhours
Plate Pair for Search	Discovery	1	10
Set of Plates	Orbit, Identification	10	1000
Many Sets of Plates	Mass	100	10000
Interferometry	Size	1	10
Spectrophotometry (0.3-1.1 μm)	Composition	1	10
One polarization measurement		1	1
Polarization as a function of phase	Size	10	10
Polarization as a function of wavelength	Texture	10	10
Absolute Photometry	Size	1	1
Photometry as a function of phase	Texture	10	10
Radar Measurement	Roughness, Composition	10	10
One Lightcurve	Spin Period, Roughness	10C ^b	100
Set of Lightcurves	Orientation of Axis; Shape Collision vs. Fragmentation; Discovery of Systematic Effect Sense of rotation	100C	1000
Infrared Measurement (10 μm , 20 μm)	Size	1C	10

Notes: ^aEstimated Times in hours.

^bC is a correction factor (~3) indicating the requirement of having perfect sky conditions.

Spectrophotometric studies of composition are new; they need extensive support from laboratory measurements. This work, and its extension beyond the 0.3 - 1.1 μm range (see Table 4-4), promises exciting new results in addition to those already obtained (for instance, the Fe^{2+} absorption found at 0.9 μm on Vesta).

Radar observations of roughness and composition have only been initiated, namely for Icarus and Toro. A great future is opening because of the resurfacing of the Arecibo dish, so that many asteroids and satellites will be observable, with resolution on the order of 1 km, as of 1975.

The determination of spin periods from asteroid lightcurves is continuing, and approximate models of the shape and roughness are being developed. As for the orientation of the rotation axis, the large investment of telescope time and in preparations/reductions is noted in Table 4-9.

Obviously, adequate funding of a ground-based cometary and asteroid research program is required to insure a proper level of research. Funding is needed to:

- (1) insure the continued participation of the scientific community
- (2) develop new ground-based instrumentation and up-date current equipment
- (3) insure adequate observing time on multipurpose observatory instruments, or to provide for telescopes, one in the Northern and one in the Southern hemisphere, and dedicated to cometary and asteroid research
- (4) support developments in theory and laboratory work.

4.3.1.3 Meteorites

The study of meteorites is intimately related to the study of comets and asteroids since most, if not all, meteorites appear to have originated in such objects. The lunar program has demonstrated that orders of magnitude

more information can be obtained by the study of returned samples in terrestrial laboratories than was obtainable by soft-landed analyzers, and an order of magnitude more information by landing missions than by remote sensing.

There are about 30 well-defined classes of meteorites with 5 or more members, and another 100 meteorite categories with 4 or fewer representatives. Thus, we have in our museums key samples of a large number of asteroids and/or comets which are capable of being studied in great detail in our laboratories. We need detailed spectroscopic observations of many asteroids and of meteorites of all types in order to define relationships between them, and 2) we need to make increased numbers of detailed laboratory studies of meteorites; they should be subjected to the same quantitative study as the lunar samples. This will ensure a maximum yield from the first asteroid and comet missions.

4.3.2 Earth Bound Orbiting Spacecraft and Rockets

Little needs to be said here for earth orbiting spacecraft and rockets except to point out that a coordinated observing program from such laboratory benches is essential to provide a comparison with in situ observations, and to increase our knowledge from such vantage points. Clearly, eliminating the terrestrial atmospheric effects is essential to provide progress in the study of these target bodies.

One area which should receive additional stress involves high altitude balloons. Information from these relatively steady vantage points would be extremely valuable in the study program for comets and asteroids.

SECTION V

PRIMARY MISSION OPPORTUNITIES

Mission opportunities for both asteroids and comets have been studied over the past several years. The most recent thinking on these opportunities is documented in the references attached to this report. However, a brief distillation summarizing the leading candidates for space missions is necessary to focus attention on timing and planning.

The total field of short period comet opportunities has been previously addressed by the IIT research Institute (See Bibliography) under their sighting criteria. They found 16 apparitions between 1980 and 2000 with what were classed as having "good" sighting conditions. This group while not including the 1970's provides an excellent summary of primary candidates. Table 5-1 lists these opportunities chronologically giving inclination, eccentricity, earth-perihelion distance, perihelion distance, number of observations, and maximum total magnitude. (Ref. 2, Atkins, Moore, 1973.)

The most attractive opportunity prior to 1980 is the previously mentioned Grigg-Skjellerup opportunity in 1977. Fast flyby trajectories to this comet have been discovered (Ref. 1, Ness, Farguhar, 1972) which carry the vehicle on to a second comet, Giacobini-Zinner. The arrival at Giacobini-Zinner occurs in 1979.

While there are more comet missions opportunities available in the next 15 years than would be programmatically reasonable to attempt, the selection options are not unlimited. This is particularly true if a sequential exploration philosophy is adopted. It is important to note that the apparitions of Encke in 1980 and 1984 constitute an infrequent pair with excellent selection attributes (See Ref. 2.) This pair must therefore be treated as unique among the opportunities.

Mission strategies for the small bodies can be broken into two categories. Ballistic missions refer to those achieved by a single, large impulse with chemical propulsion, and generally refer to fast flybys. Low thrust missions are those executed with a continuous thrust solar electric propulsion system and imply a capability to achieve slow flybys and rendezvous.

Table 5-1. Mission Opportunities between 1980 and 2000

Year	Name	Inclin. Degrees	Eccent.	Min. Earth Dist/Days Before Perihelion	Perihelion AU	No. of Observ.	Max Total Mag	Period, Yr
80	Encke	11.9	0.8467	0.277/40	0.34	49	4.5	3.3
82	d'Arrest	19.4	0.6247	0.696/30	1.29	12	10.6	6.4
82	Grigg-Skjellerup	21.1	0.6660	0.319/+16*	0.99	12	10.6	5.1
83	Kopff	4.7	0.5450	0.747/64	1.57	10	9.8	6.4
84	Encke	11.9	0.8460	0.625/+9	0.34	49	3.7	3.3
85	Giacobini-Zinner	31.7	0.7070	0.487/0	1.00	9	8.6	6.5
86	Halley	162.3	0.9672	0.618/74	0.59	27	1.5	76.0
87	Borrelly	30.2	0.6242	0.481/11	1.32	8	9.2	6.8
88	Temple-2	12.4	0.5444	0.768/80	1.38	15	11.8	5.3
91	Faye	9.1	0.5780	0.612/15	1.59	16	11.0	7.3
93	Forbes	4.7	0.5676	1.79/+100	1.45	4	10.8	6.3
93	Schaumasse	11.9	0.7030	0.591/45	1.21	6	9.0	8.3
94	Tuttle	9.9	0.8223	1.93/+25	1.12	4	7.5	5.6
95	Perrine-Mrkos	17.8	0.6360	0.723/37	1.31	5	11.3	6.8
96	Kopff	4.7	0.5450	0.566/9	1.57	10	8.8	6.4
98	Giacobini-Zinner	31.7	0.7070	0.658/+6	1.00	9	7.8	6.5

*Plus indicates days past perihelion

5.1 BALLISTIC

Ballistic mission strategies are characterized by relatively short flight times and fairly high encounter speeds. There are, however, ballistic opportunities, fewer in number, which have longer flight times but not necessarily lower encounter speeds. The primary comet candidates in the short flight time category generally include the following opportunities:

- (1) d'Arrest 1976*
- (2) Grigg Skjellerup 1977 with a possible follow on trajectory to Giacobini-Zinner, arriving in 1979
- (3) Encke 1980
- (4) Grigg-Skjellerup 1982
- (5) d'Arrest 1982
- (6) Giacobini-Zinner 1985
- (7) Halley 1986

The ballistic flight times to these targets are generally 3 to 6 months in duration. The associated trajectories stay within 1.5 AU of the sun. In these regimes solar cells would be adequate as a power source. These short flight time opportunities do imply fairly high encounter speeds. The lowest encounter speed in the set is about 7.0 km/s, occurring for the 1980 Encke opportunity. That mission, however, requires intercept very near Encke's perihelion of 0.34 AU, and implies a thermal environment equivalent to 10 to 12 solar intensities.

In the ballistic, short flight time mode, the time of launch may occur after the initial sighting for the year of perihelion passage (recovery). This, of course, would reduce the probable miss distance of a spacecraft without a significant trajectory correction capability because updates on the target ephemerides before launch would be possible. Thus, targeting errors could be taken out at launch, lessening the on-board propulsion requirement.

Another consideration is the possibility for enroute asteroid flybys. Because the short time ballistic paths generally would not go into the asteroid

* The year indicates the date of perihelion passage.

belt, chances for such flybys would not occur until after encounter. Longer flights passing through the asteroid belt are required to enhance possibilities for enroute asteroid flybys.

There are opportunities for longer flight time ballistic comet missions. The primary advantages of selecting these may involve a small reduction in encounter speed, perhaps a better choice of intercept point, and/or the opportunity for asteroid flybys enroute. These missions generally take 2 to 3 years and favor targets lying near or outside 1.5 AU, such as Comet Borelly in 1986. Of course, longer flight time missions are also available to comets with perihelia inside 1.5 AU, such as Encke in 1980.

5.2 LOW THRUST

For a sequential philosophy leading to the ultimate goal of rendezvous with either comets or asteroids, low thrust propulsion is required. Several studies in the Bibliography and references have shown the advantages of low thrust or solar electric propulsion for comet and asteroid missions. As noted in last year's report, an SEP rendezvous to Encke at its 1980 apparition could pass two asteroids, Aschera and Alekto, enroute. A slow flyby to Encke in 1980 (Ref. 15, Bender, et al, 1973) could also pass an asteroid enroute, in this case, Alwine. A slow flyby of comet Encke in 1980 would provide an early precursor leading to a rendezvous in 1984.

An additional advantage of the low thrust strategy is that the flexibility provided by the propulsion system can be used to shape the trajectory, thus moving the intercept point for the Encke mission away from the 0.34 A.U. perihelion of the comet's orbit and the attendant severe thermal environment. Because the coma shrinks as the comet approaches perihelion, an earlier intercept would significantly increase the available observation time in the comet. This would be in addition to the observing time gained from its capability to achieve a slow flyby.

While the Encke pair provides the most attractive opportunities for electric propulsion, the references show that other opportunities for electric propulsion, listed in Table 5-1, are also favorable. It should also be noted that the low thrust mission strategy would always allow enroute asteroid flybys.

Flight times for the low thrust comet and asteroid missions are generally two to three years in length, comparable with contemplated ballistic Jovian missions.

SECTION VI

VEHICULAR TECHNOLOGY

Existing vehicle technologies can be considered as to their capabilities in the various mission classes discussed above. Today there are three distinct levels of vehicular technology: 1) that with minimum flexibility and a strong emphasis toward basic particles and fields investigations, 2) that with a higher level of capability demanded of planetology investigations with imaging, longer life, etc., and 3) that which includes the higher capability science along with a rendezvous delivery system.

The minimum level technology could be applied to the short flight time ballistic comet missions. This technology is well developed and flight-proven; only a minimum of modification and further development would be required. This technology would permit basic, but limited studies of comets and asteroids, including the plasma and particle environment, magnetic fields, and thermal properties. Many very important features of comet and asteroids could not be investigated.

For greater exploration capability, a higher level of vehicle technology is required. The necessary kind of instrument technology for this level has also been developed and flight proven in the past. Slow flyby missions will enable imaging the nucleus of a comet with well-stabilized optical systems, and can make possible detailed observations of the density and composition of its coma and tail. Data storage, telemetry, attitude and pointing control, and other support systems should be capable of handling sophisticated measurements during slow flybys.

An even more demanding situation exists with rendezvous and docking missions. Flight-times for these missions are on the order of two to three years. Imaging systems, ion detectors, plasma probes, particle analyzers, thermal sensors, gravity gradient instruments, magnetic and electric field meters, and other precision instrument should have high sensitivity and resolution. The orientation of the spacecraft must be controlled and stabilized with high accuracy. The communication system must be capable of handling large

amounts of information and commands. Although similar systems have been developed for other space missions, further development of instruments for specific applications to comet and asteroid rendezvous and docking missions is paramount.

SECTION VII

RECOMMENDATIONS

7.1 FLIGHT PROJECTS

The recommendations of the Science Advisory Committee on Comments and Asteroids are:

- (1) A fast flyby mission to comet Grigg-Skjellerup (perihelion date April 11, 1977), with the follow-on flyby of Giacobini-Zinner.
- (2) A slow flyby mission to comet Encke (perihelion date on December 8, 1980) to include passage by one or two asteroids if possible.
- (3) An asteroid rendezvous in the very early 1980's possibly utilizing the shuttle as launch vehicle. Because many asteroids are available as targets, a selection can best be made late in this decade.
- (4) A comet rendezvous (probably to Encke in 1984) should follow as soon as possible.
- (5) A mission to Halley's comet in 1986. A fast flyby (55 km/sec) could be accomplished with chemical propulsion. For a slow flyby or rendezvous, nuclear electric propulsion would be required.
- (6) An asteroid docking mission to follow the Halley mission.
- (7) A comet docking mission.
- (8) An asteroid sample return mission.
- (9) A comet sample return mission.

Comet Kohoutek was discovered less than ten months before perihelion. It appears to be a great comet like Halley's. Smaller comets are being discovered every year. This emphasizes the desirability of maintaining a cometary spacecraft in launch readiness to exploit an unpredictable opportunity.

Because asteroids show great individual differences, several asteroid missions are essential for a successful program.

7.2 PROPULSION SYSTEMS

Comet and asteroid missions, with the exception of fast flybys, require a relatively large space propulsion capability for which solar electric propulsion appears to offer the only feasible technology currently under development; consequently, this Committee recommends that further development of electric space propulsion be undertaken. The availability of such a system for the first slow flyby mission to comet Encke (launching in 1979) would enormously increase the scientific value of this mission.

The space shuttle, which will become available around 1980, is a potential launch vehicle for missions in the 1980's. The availability of the shuttle could greatly simplify the maintenance of flight readiness for unexpected comet opportunities.

7.3 EXPERIMENT DEVELOPMENT

Some of the experiments deemed useful for eventual comet and asteroid missions (Section 2.0) utilize instruments which have already been flown successfully on other space flight missions and which therefore require little or no modification. These include the low field (≥ 1 gamma) magnetometer, solar-wind plasma analyzer, vidicon imaging systems ultraviolet spectrometer, infrared photometer, and photo polarimeter. Other desired experiments require instruments which have either not been designed to operate under the special conditions which apply to comet/asteroid missions or which require further development work. These include the neutral mass spectrometer, spin-scan imaging systems, the dust composition analyzer, the x-ray spectrometer, the x-ray fluorescence spectrometer, the x-ray diffractometer, and nucleus probe instruments. Finally, some of the recommended experiments appear to have multiple candidate instruments (e.g., spin-scan imaging vs. orthicon-type imaging systems) and studies will be required to determine the applicability of the various instruments to particular missions.

The committee therefore makes the following recommendations:

- (1) Neutral mass spectrometer development should be emphasized in order to ensure the capability of measuring the molecular constituents at the low densities which prevail in the coma. This

work should include the development of techniques for testing these devices under conditions which simulate the cometary environment. Particular attention should go to investigating the effect of high relative velocity on the fragmentation of neutral molecules during fast flyby missions.

- (2) Dust composition analyzers are the key experiments for determining all elements other than C, H, O and N in comet and asteroid landing missions. They require further development for use in comet/asteroid missions. Present impact-ionization composition detectors offer insufficient mass resolution, are physically larger than optimum for space flight use, and have poor ionization yields at particle velocities which are typical of slow flyby (< 5 km/sec) and rendezvous missions. It is urgent that the development of better experiments be started now, preferably by two or more competing groups.
- (3) A filter wheel - image orthicon system for taking nearly monochromatic images of the comet in various molecular emissions (e.g. CN) should be studied with regard to the necessary light intensity levels, exposure times, and the achievable photometric accuracy.
- (4) A critical comparison of vidicon-type and spin-scan imaging systems is needed. This study should establish the relative merits of these two types of imaging systems for use on spinning, de-spun, and 3-axis stabilized spacecraft, respectively. The technical suitability of these systems for terminal guidance and for imaging of cometary nuclei and asteroids should be examined. It is crucial that these studies be initiated now.
- (5) Currently available electron energy analyzers and ion mass spectrometers do not cover the range of energies and masses expected in the cometary plasma. However, the principles of charged particle optics are well known and the technology of these devices is highly advanced. Design and development of these instruments should be supported.

- (6) X-ray and γ -ray spectrometer systems, successfully used to determine the elemental composition of the lunar surface, were developed many years ago. Since then the state of the art, particularly of sensor technology has developed substantially. Further development of these instruments should be funded to promote an increase in sensitivity and resolution of these systems. Also, emphasis should be placed on functions of these instruments which were not applicable to the lunar surface but which are of interest in asteroid-comet missions. This includes the determination of hydrides such as water ice from neutron-capture resonance of hydrogen.
- (7) Instrumentation for phase analysis, specifically by x-ray diffraction, is of great potential importance for landing experiments on asteroids as well as on larger satellites and planets, and possibly on cometary nuclei. Substantial engineering developments are needed and should be initiated now.

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"A Mission Analysis Study of Comet Rendezvous and Asteroid Docking"
JPL Report 760-71, 15 June 1972.

ABSTRACT

This report surveys comet and asteroid mission opportunities and selects representative missions for detailed analysis. Criteria based on science and mission considerations are used for selection of the analysis set. Emphasis is on determination of spacecraft performance requirements for rendezvous and docking. The propulsive mode is solar electric propulsion because of its unique applicability to these kinds of missions. Six mission targets, three comets and three asteroids, comprise the set. These represent a range of comet and asteroid types. The comets are Encke, Kopff, and Giacobini-Zinner; the asteroids are Eros, Ceres, and Massalia. The missions are discussed in terms of payload, navigation, and guidance parameters. Specific science objectives and instrumentation are not treated.

"Solar Electric Multimission Spacecraft (SEMMS) Phase A Final Report"
JPL Report 617-2, 10 September 1971.

ABSTRACT

The application of solar electric propulsion to a spectrum of missions is studied. Along with terrestrial and outer planet missions, small body missions to the asteroid Eros and comet Encke are included. The mission mode for the small body missions is rendezvous. Mission analysis forms the backdrop for the hardware implementation emphasis of the study. The tenor is that of a concept feasibility study which identifies areas of concern for a follow-on implementation.

"Solar Electric Propulsion System Integration Technology (SEPSIT) Final Report"
Vols. 1, 2, 3 JPL TM33-583, 15 November 1972.

ABSTRACT

An examination of solar electric propulsion technology is the emphasis of the study. A 1980 rendezvous with comet Encke was selected for mission requirements because it was felt that if the technology could meet the requirements of the Encke mission it would be readily applicable for other, less demanding missions. The primary objectives of the work were to: 1) select a mission design point, 2) define a baseline vehicle design for studies on integration of SEP, 3) specify the thrust subsystem design, and 4) define the interfaces and functional requirements between the thrust subsystem and the total vehicle. This study provides a focus for technological assessment of SEP readiness. Volume 1 presents a summary of the effort. Volume 2 describes the mission and presents the resulting preliminary functional description. Volume 3 provides the details on the supporting trade studies and analyses.

"Halley's Comet Flythrough the Rendezvous Missions Via Solar Electric Propulsion" Report T-28, IIT Research Institute, May 1971.

ABSTRACT

The characteristics and capabilities of solar electric propulsion (SEP) for missions to Halley's comet are described. Trajectory and payload requirements are emphasized with flight time, flythrough speed, launch vehicles, SEP powerplant size, and other SEP design characteristics. Questions concerning science objectives, instruments, and total vehicular design are not treated. The objective is to delineate possibilities for an assessment of mission feasibility. However, an attractive mission profile could not be found. This resulted primarily because the relatively easy missions to Halley display high velocity flyby speeds and imply severe design requirements.

ABSTRACT

The feasibility of a mission to d'Arrest in 1976 is explored. The mission mode is ballistic with flyby speeds generally above 13 km/s. Assumptions include a standard, medium size launch vehicle and Mariner spacecraft subsystems. The primary objectives are to 1) verify the applicability of Mariner-class spacecraft for comet missions, 2) define potential science benefits, and 3) determine improvement and problem areas.

An observational history of the comet is included which forms the background for the study. Payload science instruments are suggested and support requirements are studied.

An appendix is included which discusses rendezvous possibilities and comet imaging for approach guidance. An interesting study of Comet Bennet is used to frame the approach guidance discussion.

IIT Research Institute Publications on Comet Missions:

"Perturbation, Sighting and Trajectory Analysis for Periodic Comets: 1965 - 1975" Report T-7, 1964.

"Sighting and Trajectory Analysis for Periodic Comets: 1975 - 1986" Report T-11, 1965.

"A Survey of Comet Missions" Report M-7, 1965.

"Trajectory and Sighting Analysis for First Apparition Comets" Report T-13, 1965.

"Cometary Study by Means of Space Missions" Technical Memorandum M-8, 1965.

"Missions to the Comets" Report M-9, 1965.

"Trajectory and Propulsion Characteristics of Comet Rendezvous Opportunities" Report T-25, 1970.

ABSTRACT

This series of reports by the IIT Research Institute of Chicago was completed for NASA's Office of Space Science. The reports cover a wide spectrum of considerations for comet missions. Selection criteria, mission strategies, and trajectory and performance parameters are examined to varying levels of technical detail. These reports provide an excellent overview.

"A Feasibility Study of Unmanned Comet and Asteroid Rendezvous and Docking Concepts Using Solar Electric Propulsion (CARD)," Northrop Services, Inc., NAS8-27206, 15 October 1971.

ABSTRACT

This study investigated mission/system feasibility for rendezvous, docking, and sample return missions to the comet Encke and asteroid Eros. The vehicle concepts developed utilized solar electric propulsion and Tital IID class launch vehicles.

The study defined science objectives, candidate science payloads and some baseline and alternative mission/system concepts. A conclusion of the study was that an SEP concept with a staged Rendezvous, Docking, Science, and Sampling (RDSS) module is attractive for sample return mission applications and that SEP at 19-KW power can perform an Eros sample return mission launched in 1977 and a one-way Encke rendezvous mission launched in 1978. The Encke sample return mission requires a 27.5 KW propulsion system and 6 years round trip time. It was also concluded that the unknown nature of the Encke nucleus and surrounding environment make a precursor mission highly desirable before attempting a sample return mission.

"A Study to Define Unmanned Comet and Asteroid Mission Opportunities and Characteristics Using Solar Electric Propulsion," Report No. TR-250-1169, Northrop Services, Inc., NAS8-28427, 15 December 1972.

ABSTRACT

The purpose of the study was to provide mission selection and planning data for assessment of missions possible in the 1980's. Data is contained in the catalog for 250 comet and asteroid rendezvous and flyby missions. A nominal 18 KW mission was defined for each target opportunity and sensitivity to major mission parameters determined. In addition, major geometric and dynamic trajectory histories are depicted for the nominal mission and, for comet targets, tables of potential asteroid flybys enroute to the baseline comet rendezvous are included.

Solar Electric Propulsion is specifically applicable to all mission opportunities contained in the catalog. The catalog presents data sufficient for a gross assessment for Shuttle/Centaur and Titan 3E/Centaur launch. The user may also convert data to other launch vehicles from the basic catalog data.

"Study of Comet Rendezvous Mission," TRW Report 20513-6006-R0-00, Volume I and II, May 12, 1972, JPL Study Contract No. 953247.

ABSTRACT

Scientific objectives, modes of exploration and implementation alternatives of a low-thrust rendezvous mission to Encke's comet in 1984 were studied with emphasis on developing the scientific rationale for such a mission, based on available knowledge and best estimates of this comet's physical characteristics. A main section of the report is a compilation of these data, giving an up-to-date model of Encke's phenomena. (Note: A later physical model is available in Reference 5, Taylor, 1973).

Evaluation of alternative mission modes and tradeoff of performance characteristics led to formulation of a preferred exploration strategy which includes extensive maneuvering within the comet's envelope to explore coma, tail, and nucleus. This mission is performed by a 17.5 kW solar electric

propulsion spacecraft (using 13 kW for propulsion purposes), which carries 60 to 80 kg of scientific instruments. Launched in December 1981 by a Titan IIIE/Centaur booster and arriving at the comet in February 1984, 40 days before perihelion passage (nominal flight time 800 days), the spacecraft will stay in the comet envelope for at least 80 days. The residence time can be extended by several hundred days for additional scientific observations during the comet's dormancy.

"Study of a Common Solar-Electric-Propulsion Upper Stage for High-Energy Unmanned Missions," TRW Report No. 16552-6006-R0-00, Vol. I and III, dated 14 July 1971 under NASA Study Contract NAS2-6040.

ABSTRACT

This study of a multi-mission solar electric propulsion vehicle included rendezvous missions to comets and asteroids as mission objectives, i.e., a 950-day mission to Comet Encke launched in March 1978, a 750-day mission to Comet d'Arrest launched in August 1980, and a 700-day mission to Ceres launched in October 1976. A versatile spacecraft designed for application in a variety of missions permits amortization of development and reduction of recurring cost. The 17.5 kW spacecraft, launched by a Titan IIID/Centaur or Titan IIID/Burner II booster, has an injected mass ranging from 1500 to 2500 kg and carries up to 500 kg of attached or separable payload packages. A large payload stowage volume is provided.

High-energy missions beginning in the late 1970's are studied namely a Mercury orbiter, a close approach solar probe, and a high-inclination extra-ecliptic probe, in addition to asteroid and comet rendezvous missions. Alternate missions studied are high-data-rate Mars and Venus orbiters and outer planet flybys and orbiters. Still more advanced missions such as surface sample return from Mars or the asteroid Eros, and the very difficult rendezvous with Halley's comet in 1986 were also briefly investigated. The study included analysis of mission characteristics, scientific objectives and payload requirements, design tradeoffs and interface studies, and definition of a configuration concept that meets the specified mission objectives.

"Study to Adapt Solar Electric Propulsion to the Pioneer F and G Spacecraft," TRW Report No. 22125-6001-R0-00, dated October 15, 1972, prepared for NASA/Ames Research Center under Contract NAS2-6796.

ABSTRACT

This study, concerned with the feasibility of adding an electric thrust subsystem to the spin-stabilized Pioneer F/G spacecraft, showed that improved performance capability is obtained for certain missions. The evaluation was performed for Atlas and Titan launch vehicles with Centaur and TE-364-4 upper stages and for electric thrust stages of 8- and 5-kW.

A variety of missions were evaluated ranging from a direct solar approach mission to 0.14 AU to a flyby of Neptune. Performance improvements were obtained for all missions evaluated. The most significant improvement was for a 1000-day rendezvous mission to Comet Tempel 2. Electric propulsion is particularly performance-effective in missions where a major maneuver must be performed without the assistance of a large local gravity well as in comet and asteroid rendezvous.

Addition of solar electric propulsion to a spinning spacecraft such as Pioneer had not been previously investigated because of apparent implementation difficulties. However, the study showed that satisfactory design solutions can be found that involve only small performance penalties in terms of solar array and thrust pointing efficiency.

The required Pioneer design modifications included the addition of a medium-gain axial-symmetric fan-beam antenna, a terminal guidance sensor, as well as electric propulsion hardware and a centrifugally deployed pair of solar panels replacing the radioisotope power source.

"Comet Intercept Study," Space Technology Laboratories Report No. 8668-6002-RU-000, Vol. I and II, 28 March 1963, NASA Study Contract No. NASW-414.

ABSTRACT

This report contains data on orbital and physical characteristics of 31 comets and examines the feasibility of ballistic flyby missions in the 60's and 70's. Mission maps and launch constraints are presented for each flight opportunity. The report gives a comprehensive listing of flight opportunities and requirements; presents scientific objectives, mission profiles, along with spacecraft design characteristics; and discusses midcourse and terminal guidance requirements. A spin-stabilized 430 pound spacecraft launched by an Atlas-Agena booster was envisioned.

"Feasibility Study for a Solar Electric Propulsion Stage and Integrated SEP Spacecraft," Report, dated March 27, 1972. Rockwell International, Inc., Contract NAS8-27360.

"Feasibility Study for a Solar Electric Propulsion Stage," Report, dated January 19, 1973. Rockwell International, Inc., Contract NAS8-27360.

ABSTRACT

Studies to examine the feasibility of utilizing a Solar Electric vehicle for accomplishing a broad range of high-energy planetary missions (including comet and asteroids) began in 1971. The SEP stage in combination with spacecraft is deemed cost effective. The study indicates that it is possible to build a single solar electric propulsion concept to accomplish the range of missions investigated. Later studies have broadened applications to include geosynchronous earth orbit missions.

Comet and asteroid missions investigated are a 1980 Encke Slow Flyby Mission, a 1984 Encke Rendezvous Mission, and a Ceres Orbiter Mission which arrives in 1985.

The payload for the Encke Slow Flyby Mission is the science package defined in Reference 10.

"Asteroid and Comet Exploration," NASA CR-2291, July 1973; MSFC Contract NAS8-27929 with University Research Foundation and University of California, San Diego, September 1971 to July 1973.

ABSTRACT

The scientific goals in terms of the significant physical and chemical properties of missions to comets and asteroids, including a mission strategy, are outlined and discussed. The experiments and instrument type for accomplishing these goals are given assuming that three types of missions will be used: flyby, rendezvous, and docking.

Five targets of immediate interest that have been identified are:

- (1) Asteroidal or extinct cometary bodies in near-Earth orbits (Apollo and Amor objects).
- (2) Main belt asteroids with widely differing surface compositions.
- (3) Cometary structures and meteor streams.
- (4) Resonance bound objects in the orbits of giant planets.
- (5) Satellites small enough to ensure preservation of their source material.

An appropriate exploration program would concurrently emphasize flight missions to comets and asteroids and intensified earth-based and earth-orbit studies of these bodies. A logical progression of flight missions would aim first at remote analyses by fast and slow fly-by, rendezvous, and, finally, landings. In order to fully and accurately extract the wealth of information stored in extraterrestrial bodies, samples must eventually be collected and returned to Earth. The development of unmanned vehicles capable of such operations is stressed as crucial to the primary goals of solar system exploration.

ABSTRACT

This report discusses the feasibility, scientific objectives, mission profile characteristics, and implementation of an asteroid belt exploration mission by a spacecraft guided to intercept three or more asteroids at close range. With the abundance of possible targets in the asteroid belt a large number of such mission opportunities exist the year round. A few opportunities have also been identified where a comet can be included among the targets.

A principal consideration was to adapt available and flight-proven spacecraft design such as Pioneer F and G, augmenting its propulsion and guidance capabilities and revising the scientific payload complement in accordance with required mission characteristics. The study determines how much spacecraft modification would be necessary to meet mission requirements. A ground rule held design changes to a minimum and utilized available technology as much as possible. However, with mission dates not projected before the end of this decade, a reasonable technology growth in payload instrument design and some subsystem components is anticipated and was incorporated in the spacecraft adaptation.

A modified Pioneer spacecraft is envisioned with gross weight of 970 pounds, including 340 pounds of hydrazine for retargeting and terminal guidance maneuvers. This vehicle provides a science payload capacity of 75 pounds. The launch vehicle is Atlas/Centaur/TE364-4. The RTG power sources of Pioneer F/G are retained. The communications and data handling subsystems are modified to provide the increased telemetry bit rate (32.8 kbps) required by an uprated imaging system and other asteroid observation instruments.